9. CRYOGENICS AND SUPERCONDUCTIVITY

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Currently, the electrical industry is showing increasing interest in applications involving cryogenic temperatures. This interest is due to the decreasing electrical resistance of most conductors with decreasing temperature, which thus provides a considerable power savings. NASA is deeply involved in several areas of technology pertinent to this field. Conductors at low temperature, for example, are being used in high flux magnets. Storage and handling of cryogenic fluids required for such low temperatures are now routine. Information gained from the NASA efforts in these and other fields may be of future value to the electrical industry, such as in the design of low-temperature power transmission lines or other low-resistance devices.

An example of the effect of low temperatures on electrical resistance (in this case, for copper) is shown in figure 9-1. The electrical resistance ratio plotted is the ratio of the resistance of the conductor at any temperature to the resistance of the conductor at 492° R (i.e., the freezing point of water). The dashed curve is for common annealed copper, while the solid curve is for copper of 99.999-percent purity. For copper, as for most conductors, most of the change in resistance occurs at temperatures below about 150° R, with the resistance dropping rapidly before leveling off at some lower value. This final lower value of the resistance is called the residual resistance, and the more the material is refined, the lower the absolute value can be. All good conductors, such as copper or aluminum, show this decrease in electrical resistance of several orders of magnitude or more between room temperature and temperatures near absolute zero. Some materials, however, exhibit another phenomenon as absolute zero is approached, as illustrated in figure 9-2.

In this case, for tin of high purity, the resistance drops to zero at a certain critical temperature. This phenomenon is typical of many pure metals, alloys, and compounds, which as a class are called superconductors. Generally, the critical temperatures are close to absolute zero. There are a few superconductors, however, which have somewhat higher critical temperatures. Niobium, at about 16° R, is the best of the pure metals. Higher critical temperatures can be achieved only by using an alloy or a compound. For example, Nb_3Sn becomes superconductive at about 33° R, a critical temperature twice as high as that of niobium.

Achieving the low temperatures of interest, for either normal conductors or superconductors, requires some type of refrigeration fluid. The liquid ranges of several fluids of interest are shown in figure 9-3.

Liquid methane and liquid nitrogen are common cryogens, used for a number of purposes. For example, they are useful as shield fluids; that is, they can be used to intercept heat and hence reduce the heat input to a colder fluid, with a resultant reduction in refrigeration requirements. As primary refrigerants, however, they provide only a small decrease in the resistance of conductors. The largest decrease in electrical resistance is obtained at temperatures below about 50° R; thus, neon and hydrogen are the cryogenic fluids usually considered for normal conductors. Currently, for the superconductors, a fluid with a liquid temperature range below 33° R is required, and, for all practical purposes, only helium can be considered. At Lewis, all these cryogenic fluids are in use today for a large variety of applications.

CRYOGENIC MAGNETS

One application, involving the use of liquid neon, is the large cryogenic magnet shown in figure 9-4. The coil section is shown in figure 9-5 in more detail. With a 1-foot-diameter bore, this magnet has a field of 160 000 gauss. With a bore of $4\frac{1}{2}$ inches, the field is 200 000 gauss.

High-purity aluminum (99.999 percent) is used in the magnet as the conductor. This purity was the highest that could be obtained without zone refining. The aluminum is made in the form of a long strip, rolled circumferentially around the bore. Each aluminum turn is reinforced with stainless steel to carry the load out to the external reinforcing ring. The loads can be quite high because of the high magnetic pressures. For example, a magnetic field of 150 000 gauss is equivalent to 14 000 pounds per square inch of gas pressure within the bore.

Between each turn are small channels to allow passage of liquid neon, and the cooling is accomplished by pool boiling. In practice, the whole core assembly is merely submerged into a bath of liquid neon, which is allowed to boil as necessary to dissipate the generated heat. The power consumption of this magnet is only about 1 megawatt at a current of 15 000 amperes. Operation of the magnet at liquid-neon temperature uses approximately one-twentieth as much power as operation at room temperature. Because the current density in the conductor is 15 000 amperes per square centimeter, the device is also considerably smaller than a room-temperature magnet of the same field strength.

The neon-cooled cryogenic magnet was fabricated and installed in 1964. In 1967, the superconducting magnet, as shown in figure 9-6, was put into operation. The magnet itself is the cylinder at the bottom of the figure. The tube in the center is the support tube for the magnet, with the upper end being cooled by liquid nitrogen contained in the upper tank. This cooling reduces heat leak down the support tube. The entire magnet assembly is suspended inside a liquid helium tank for cooling of the superconductor. Electrical leads are cooled by helium boiloff gas before they pass through the nitrogen bath in the upper tank. This procedure is used to reduce heat leak to a minimum.

This magnet has a bore 6 inches in diameter by 15 inches in length and operates with a field of 140 000 gauss at a current of 90 amperes. Because the magnet is superconductive, the power is zero after the initial field is generated. A total of 55 miles of superconducting ribbon, 0.090 inch wide by 0.0003 inch thick, are used in this magnet. The superconductor itself is Nb_3Sn vapor deposited onto each side of a stainless-steel ribbon which is 0.0025 inch thick.

In operation, care must be taken to ensure that the superconductor does not become normal. In addition to a critical temperature, a superconductor also has a critical current and a critical magnetic field - either its own field or an external field, as shown in figure 9-7. Thus, there is a bounded region within which superconductivity exists. At the boundary, or surface, of this region, the material loses its superconductivity sharply, and outside the critical surface the material is a normal conductor. When a conductor is selected, all three variables must be considered. For example, in addition to the temperature, the current must be sized so that the generated magnetic field is less than the critical field. This problem, however, usually exists only for devices such as magnets.

In use, even though a superconductor is designed to operate within the critical region, there may be local fluctuations in current and magnetic field or variations in temperature at localized spots. The result will be that the superconductor becomes resistive (i.e., becomes normal) over a short length. To guard against this event, one approach is to have a copper backup of sufficient cross-sectional area to carry the current until conditions stabilize and the superconductive condition is regained.

Some examples of the techniques used for providing this copper backup are shown in figure 9-8. On the left is a typical superconducting ribbon; Nb_3Sn is vapor deposited over stainless steel, and copper is applied to both sides of the ribbon. On the right, NbTi superconductor wires are embedded in copper.

Fine wires are generally used to obtain as much surface contact with the copper as possible. The whole cable can be extruded to any desired size or shape. For example, a pipe for containing the liquid helium coolant might be made from the cable.

In addition to lowering resistive losses, the use of cryogenic temperatures also provides the advantage of extreme compactness. Figure 9-9 shows three conductors, each rated at 1500 amperes. In the case of the room-temperature copper conductor, seven cables of 0.75-inch diameter are necessary to achieve the current capability of 1500 amperes, while only one aluminum cryoconductor and one superconductor are required. A relative comparison of their total cross-sectional areas is shown in figure 9-10. The current density of the room-temperature cable is only 100 amperes per square centimeter, while the current density of the aluminum strip is approximately 15 000 amperes per square centimeter. The superconductor, however, has a current density of about one million amperes per square centimeter. As a result, superconductive devices are very compact in addition to having zero resistive power requirements.

However, although no heat is generated by the superconductive device itself, there will be heat leak into the system, and this leak will result in a small power requirement for replacement of the helium boiloff.

CRYOGENIC HANDLING AND STORAGE

To supply the liquid helium and the liquid neon used for the magnets, a liquefaction plant was built at Lewis. Figure 9-11 presents a sectional view of the plant showing the neon liquefier and the two helium liquefiers. The large storage bag outside the plant is used for conservation of the helium boiloff. The total helium liquefaction capacity is 250 liters per hour, and the neon liquefaction capacity is 60 liters per hour.

In addition to being used for the superconducting magnet, liquid helium is also used in the Centaur rocket vehicle to prechill the liquid-hydrogen pumps prior to launch. The liquid helium is air transported, as shown in figure 9-12, from Lewis to Cape Kennedy for this operation. This method of shipping liquid helium in a 5000-gallon Dewar has been in operation for several years and is an example of how such cryogenic fluids have progressed in only a short period of time from laboratory systems to operational use.

Indeed, contributing to such growth within the cryogenic industry has been the requirement by NASA for large quantities of liquid hydrogen as a rocket propellant. Only a few years ago, liquid hydrogen was not commercially available, nor were cryogenic components such as valves or instrumentation available. Today, production capacity has grown to almost 200 tons per day, and components for both ground systems and flight systems are on the commercial market.

Figure 9-13 shows some typical components in a 2-inch liquid-hydrogen transfer line. This system is entirely vacuum jacketed, and conventional hand valves and vacuum-jacketed flexible hoses for attachment to trailers and rail cars are shown.

The sizes of the components for some of our testing can also become quite large, however. Figure 9-14 shows a 14-inch unjacketed liquid-hydrogen valve. This particular valve is rated for pressures up to 1800 pounds per square inch.

Components such as these are shown to indicate the extent to which technology in the field of cryogenics has advanced. Based on such liquid-hydrogen technology, liquid-helium handling problems have been remarkably few.

Another area in which technology has advanced rapidly has been that of cryogenic storage. Figure 9-15 shows a 200 000-gallon liquid-hydrogen storage tank at the Lewis Plum Brook facility. Alongside the building are two 34 000-gallon railroad cars. The fixed tank has a boiloff loss of only 0.05 percent per day; thus, almost 6 years would be required for the entire contents to boil away.

To achieve high efficiency, storage vessels such as these require the use of extremely good insulation. The type of insulation used is the so-called multilayer or superinsulation system, as shown in figure 9-16. This type of insulation has undergone extensive development by NASA as part of its liquid-hydrogen program. The system consists of alternate layers of highly reflective radiation shields and low-conductivity spacers. The spacers not only are made of low-thermal-conductivity material but also are selected to give many point contacts with the shields. Such point contacts provide high resistance to heat flow. To be effective, the system must also be evacuated to decrease the gas conduction. The net result is that radiation becomes the primary mode of heat transfer, and the highly reflective shields will minimize such radiation.

The effectiveness of evacuating the multilayer insulation is shown in figure 9-17. Thermal conductivity is plotted as a function of gas pressure within the insulation. Also shown are curves for three other families of cryogenic insulations. Multilayer insulation, when unevacuated, is not an efficient insulation. Glass fiber batting, foams (such as polystyrene), or fine powders are better; that is, they have lower values of thermal conductivity. When evacuated, however, multilayer insulation becomes better than its closest competitor (powder) by a factor of about 40.

Necessary to high efficiency of the multilayer insulation is the highly reflective, or low-emittance, shield. Some typical shields are shown in figure 9-18. Aluminum foil, in thicknesses from 1/4 to 5 mils, was first used as a shield, but the thin foils were fragile and easily torn, while the thick foils were heavy. An improvement over aluminum foil was the development of aluminized Mylar - either coated on one side or on both sides. Commonly used is 1/4-mil Mylar with coatings of about 1000 Å thickness. These foils have a tear strength far superior to that of the aluminum foils, and they are also considerably lighter in weight. Current research is evaluating the desirability of using a gold coating in place of aluminum to obtain a lower emittance.

The other important element of multilayer insulation is the spacer. Some typical spacers are shown in figure 9-19. When Mylar (aluminized on only one side) is used as a shield, the Mylar can also serve as the spacer. This spacing can be accomplished by embossing or crinkling the single aluminized Mylar film to produce random small area contacts that create a high thermal resistance. This method of spacing can only be used with radiation shields of low conductivity (e.g., Mylar film) coated with reflective metal on only one side. This method also has the disadvantage of providing an insulation system that is sensitive to compressive loads.

The other two spacers in common use are glass paper and glass fabric in thicknesses of about 3 mils. The small fibers in these materials provide many point contacts and hence present a high resistance to heat flow. Under investigation are many other types of spacer, such as thin slices of foam or layers of silk netting. Weight, compressive load on the insulation, environment, cost, and method of installation must all, of course, be considered in the final selection.

These multilayer insulations can be applied in a number of ways. Figure 9-20 shows one method. In this commercial application, a large tank is being turned on a mandrel while the aluminum foil shields and glass-fiber spacers are fed from rolls arranged down the length of the tank. After wrapping is complete, the tank and its insulation will be placed into an outer metal shell to make a vacuum jacket. This type of application could also be used to insulate sections of pipe such as might be required for a helium pipe in a low-temperature power transmission line.

An alternative method of applying the multilayer insulation is to form it into blankets. In figure 9-21, extremely thick blankets are shown being installed in the vacuum space of the 200 000-gallon liquid-hydrogen tank shown in figure 9-15. Blankets are also used on flight-type tanks (fig. 9-22). In this case, nylon threads and Mylar tabs are used to form a quilted blanket of alternate layers of aluminized Mylar shields and glass paper spacers. The blankets are held to the tank surface by fasteners spaced at appropriate intervals and by an outer bag of Dacron netting. It has been calculated that this tank, when insulated and filled with liquid hydrogen, could go unvented for 200 days while in transit from Earth to Mars.

On a more down-to-earth application, multilayer insulation is currently being used on liquid-helium Dewars which are shipped, unvented, by boat from New York to Amsterdam and other European ports.

CRYOGENIC POWER TRANSMISSION LINES

Such remarkable effectiveness for multilayer insulation may lead to its use in low-temperature superconducting power transmission lines, such as shown conceptually in figure 9-23. The superconducting cable is shown in coaxial form, with the cable itself forming pipes for the helium coolant. Surrounding the pipe is the multilayer insulation. To reduce the heat load into the helium, a liquid-nitrogen-cooled heat shield is shown around the insulation. This procedure ensures that the helium insulation experiences a warm boundary temperature of only 140° R. Multilayer insulation is also shown around the heat shield to reduce the nitrogen heat load. Finally, the outside pipe serves as the outer vacuum-tight jacket.

Vaporizing liquid helium is used in this conceptual model to keep the cable at approximately 8° R, with the vapor returning back to the refrigeration plant in the gaseous-helium line. The use of vaporizing liquid helium will probably present some problems with two-phase flow in the pipe, and liquid-vapor separators will probably be required periodically down the line. An attractive alternative concept that avoids these problems would be the use of supercritical helium for cooling instead of vaporizing liquid helium.

If liquid helium were to be used, the initial quantity required for just filling the line might be somewhat large. As an example, a pipe 2 inches in diameter and 1000 miles in length would use approximately one-tenth of the 1967 annual helium production. The cost, however, would be only about four million dollars, based on estimates for future liquid-helium costs. This amount would probably be very small compared with the overall cost of the line.

The heat shield, or radiation shield, is cooled by vaporizing liquid nitrogen, and it intercepts the radiant heat from the external shell, which would be at Earth ambient temperature. The heat intercepted by the metal shield would be conducted to the nitrogen pipes; thus, the nitrogen would not have to be placed in large, expensive, annular pipes.

Again, several alternatives to this shield design could be considered. Two possibilities are all-gas cooling or all-liquid cooling with no vaporization. Another possibility would be to use liquefied natural gas in place of liquid nitrogen. Current studies are evaluating the economics of building pipelines for liquefied natural gas. The equipment, techniques, refrigeration plants, and pumping stations developed for such pipelines could be used for low-temperature power lines. An intermediate shield cooled by liquid hydrogen could also be considered.

The outer vacuum shell surrounding the whole cable system could merely be a concentric pipe, as shown, or it could have flanges down the side to permit easier cable installation and maintenance. The vacuum itself could be obtained by using mechanical roughing pumps for start-up and then using cryopumping after chilldown. The cold helium pipe will make an excellent cryopumping surface and would freeze out all gas constituents with the exception of helium. To remove the helium molecules, either left from the initial gas or from small leaks, ion pumps or cryosorption pumps could be used. Since both annular spaces require evacuation, the radiation shield must be perforated, as indicated, to allow passage of gases.

The multilayer insulation is conceptually shown as being wrapped around the pipes. In any final design, however, this method of applying multilayer insulation would have to be evaluated against alternative concepts, such as the use of blankets. Equally important would be the evaluation of field or factory application. Cost and ease of maintenance or repairs would be important considerations in the final evaluation.

The effectiveness of multilayer insulation for this conceptual design can be illustrated by figure 9-24. For a 2-inch-diameter helium pipe, total refrigeration power for both helium and nitrogen is shown as a function of insulation thickness. In this example, conservative values of the many variables, such as the insulation performance, are assumed. Several different configurations of the model are considered, as shown by the curves.

The dashed curve is for the special case of no nitrogen shield, with the outer vacuum jacket being spaced from the helium pipe by a distance equal to the thickness of the insulation on the helium pipe. As can be seen from the curve, small amounts of helium insulation are quite effective in lowering the power requirements from the large zero insulation value.

The particular condition of using only a nitrogen shield spaced 2 inches from the helium pipe (with the outer jacket spaced 3 in. from the nitrogen shield and with no helium or nitrogen insulation in the system) is shown by the circled point indicated on the ordinate. Comparing that value of power with the dashed curve shows that only about 2 inches of helium insulation would be required to be equal to a single nitrogen shield. The complexities of two separate refrigeration systems would thus be avoided.

However, as shown by the two lower curves, using insulation on the nitrogen shield appears to offer the most potential for reducing refrigeration power to a minimum. The amount of insulation required is not large; for example, 1 inch of insulation between the nitrogen shield and the outer jacket would lower total power requirements by a factor of about 6. If in addition to insulation over the nitrogen shield, insulation between the helium pipe and the nitrogen shield were also to be used, the total power requirements could be lowered even more - but only to a small extent, as shown by the two curves. Even 2 inches of helium insulation would only lower the power by approximately 3 kilowatts per mile of transmission line as compared with the condition of using only an insulated nitrogen shield with no helium insulation.

Obviously, final determination of the amount of insulation desirable and its location in the system would depend on economic trade-offs between overall initial costs and refrigeration plant operating costs, with such trade-offs being made for much more detailed designs than the simple conceptual model shown. Indeed, many detailed engineering design optimizations and cost studies would be necessary for all elements of the transmission line system to attain the final line design. No attempt has been made herein to do such detailed design and evaluation. Only one area, that of multilayer insulation, has been examined. These brief calculations do tend to indicate, however, that multilayer insulation, as available today, is worthy of consideration in the design of a superconducting power transmission line. Even if a normal conducting line operated at liquid-hydrogen temperature were desired, many of the same considerations as brought out by this conceptual model would still apply.

SUMMARY

NASA is involved in several areas of cryogenic technology which may be of potential interest to the electrical industry. Magnets built of superconducting materials are in routine operation. Cryogenic fluids, including liquid helium, are being produced and handled on a large-scale commercial basis. Cryogenic insulation technology is well advanced. Information from all these areas may be useful in making cryogenic power lines or other low-temperature electrical equipment a future economic possibility.

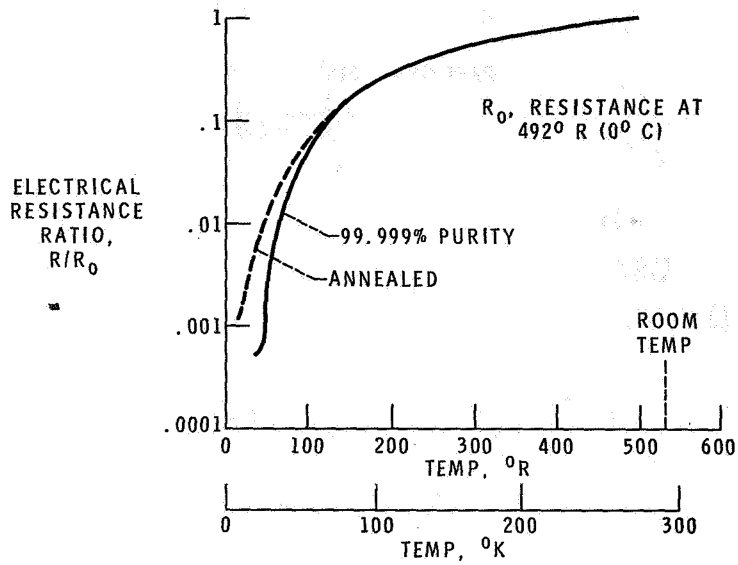

Figure 9-1. - Electrical resistance of copper.

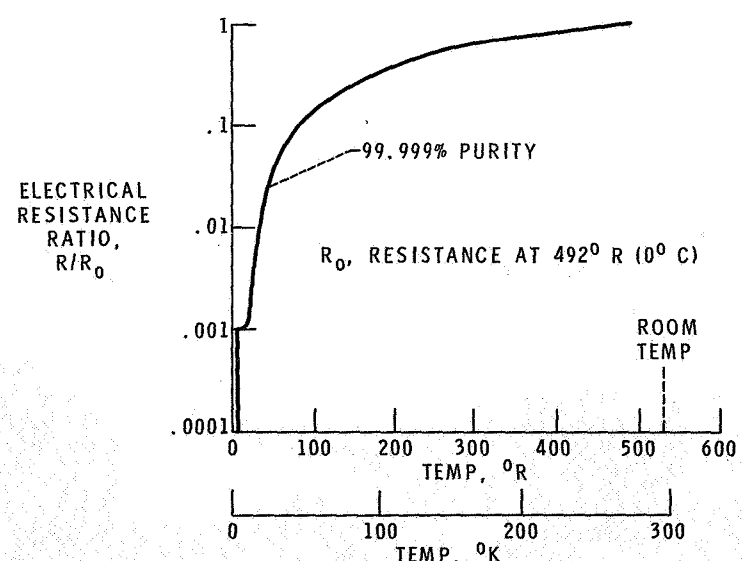

Figure 9-2. - Electrical resistance of tin.

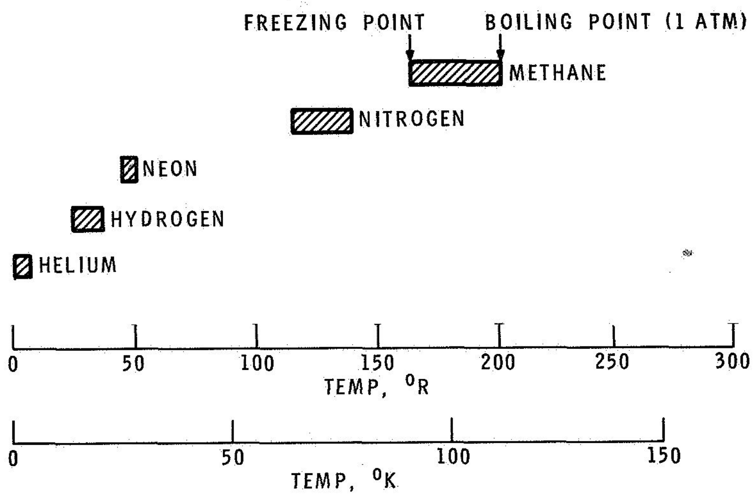

Figure 9-3. - Liquid temperature range of cryogenic fluids.

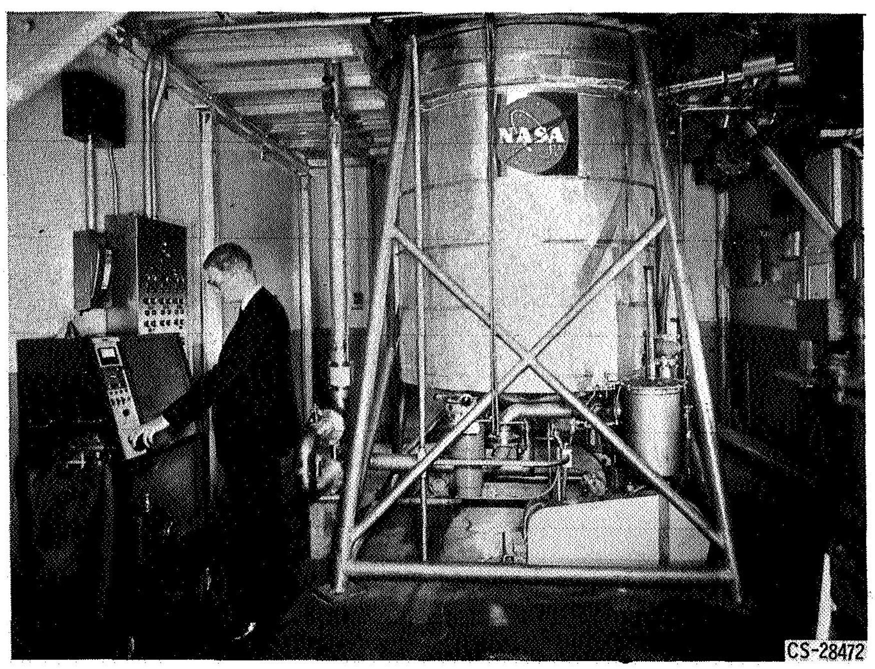

Figure 9-4. - Neon-cooled cryogenic magnet.

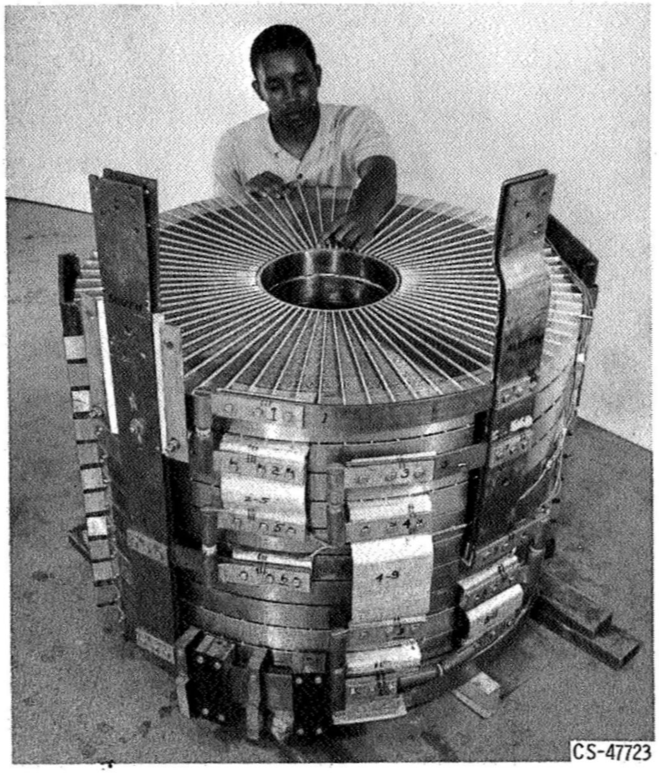

Figure 9-5. - Neon-cooled electromagnet coil assembly.

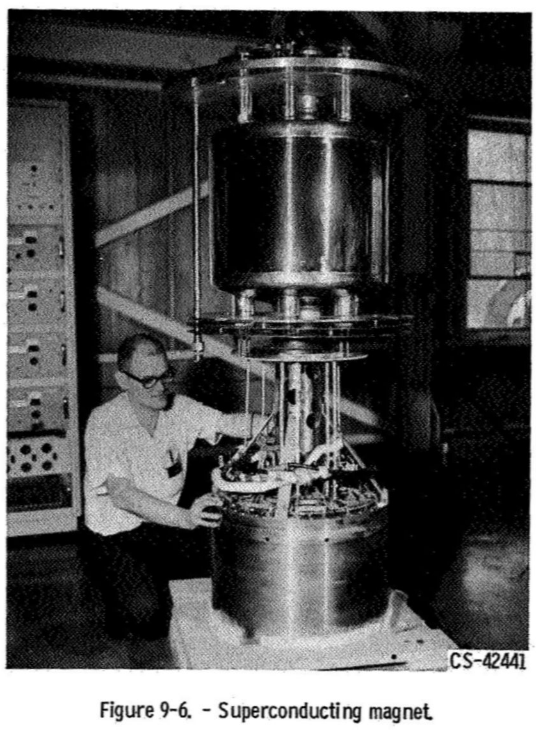

Figure 9-6. - Superconducting magnet.

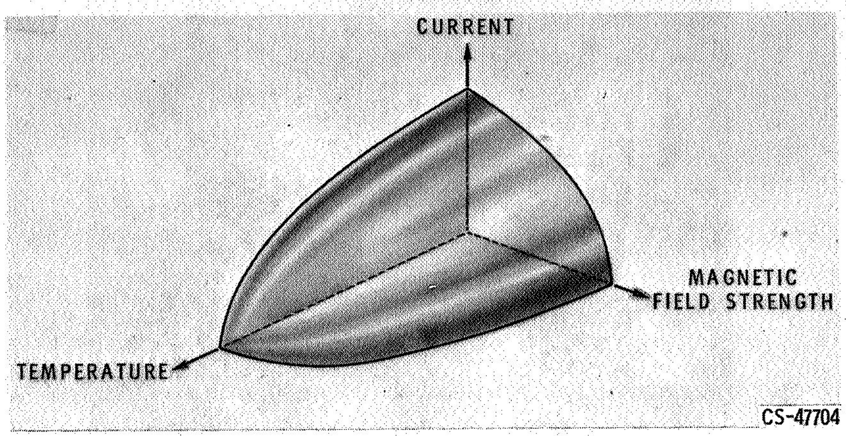

Figure 9-7. - Critical surface of superconductor.

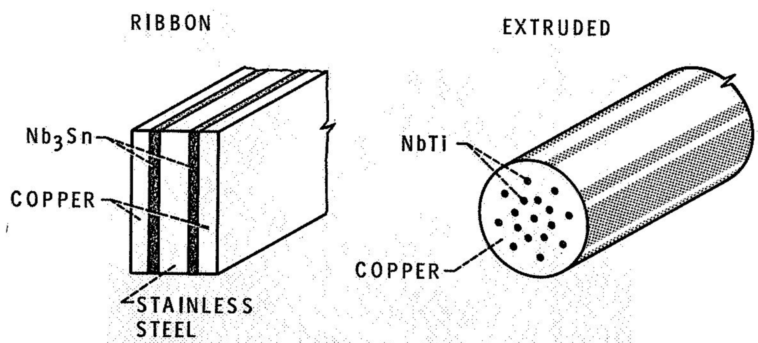

Figure 9-8. - Typical cross sections of superconducting cables.

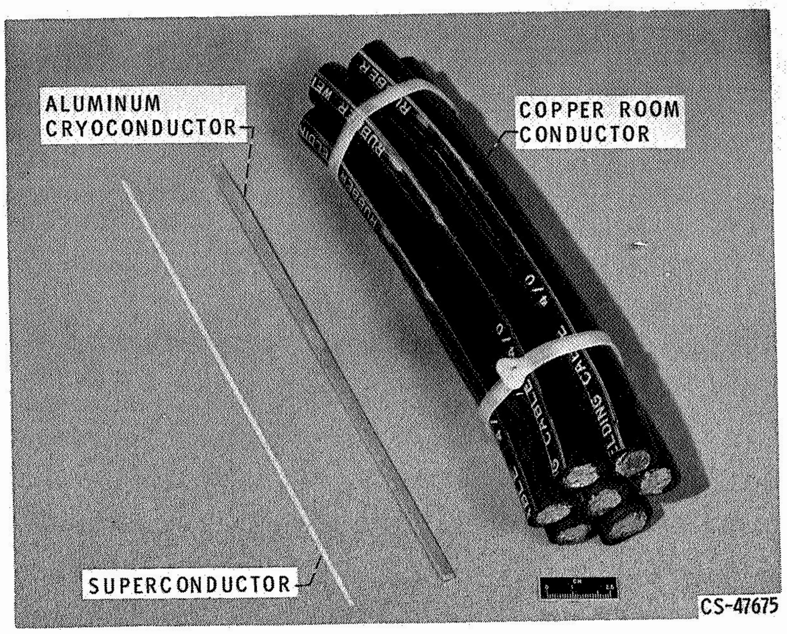

Figure 9-9. - 1500-Ampere conductors.

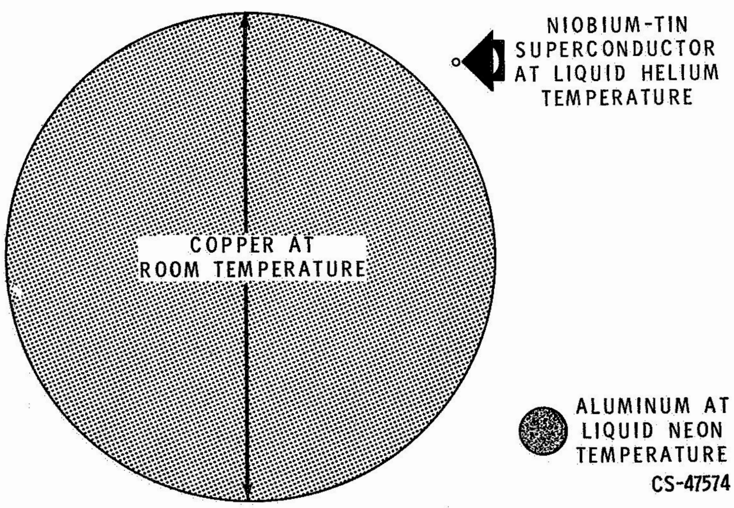

Figure 9-10. - Comparison of conductor areas.

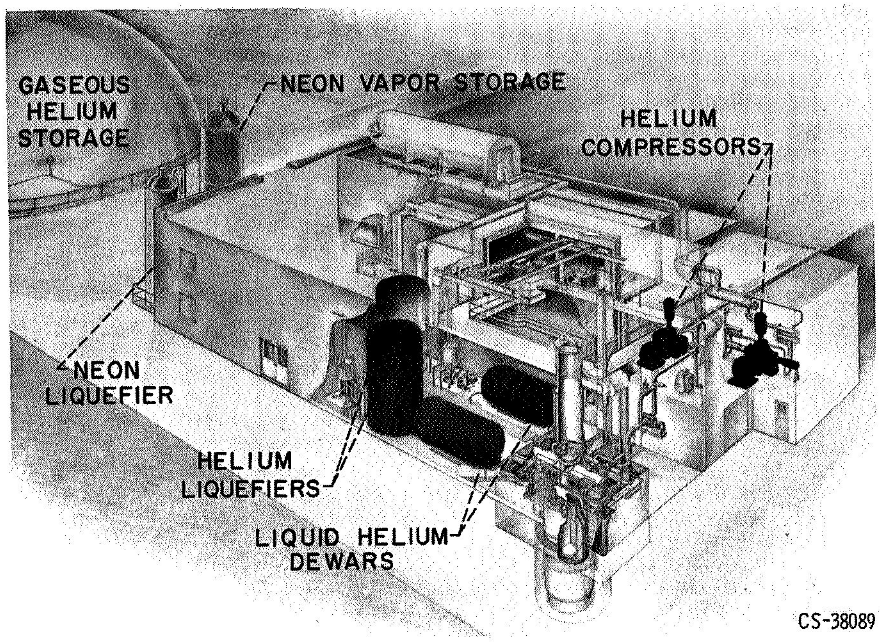

Figure 9-11. - Helium liquefier.

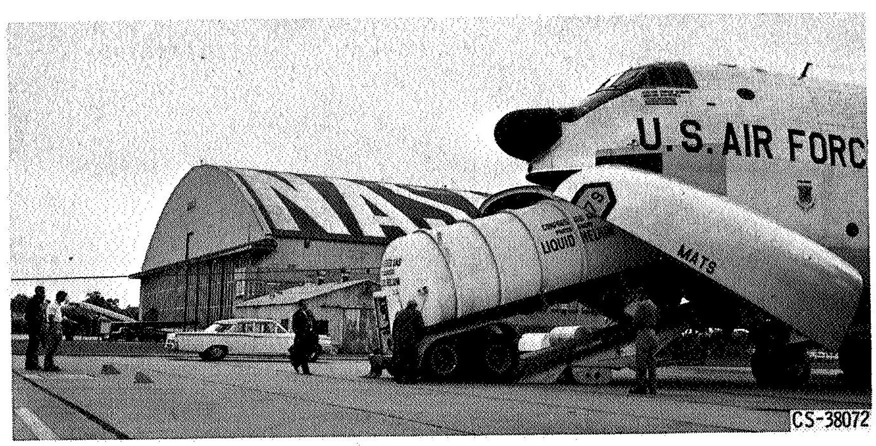

Figure 9-12. - Air transport of liquid helium.

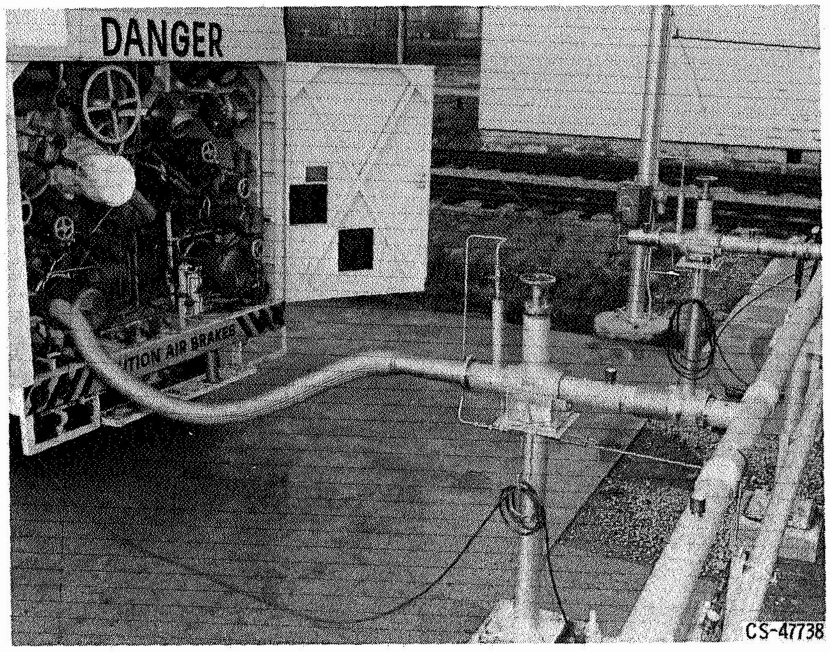

Figure 9-13. - Flow-line components.

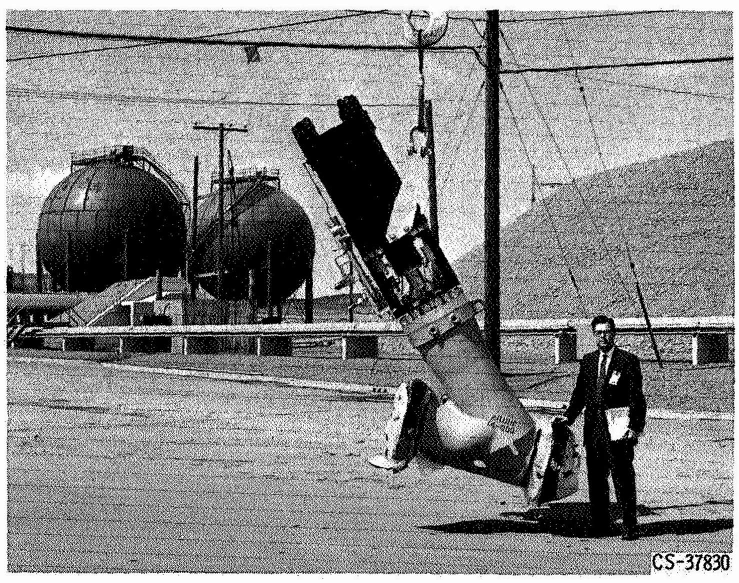

Figure 9-14. - 14-Inch plug valve.

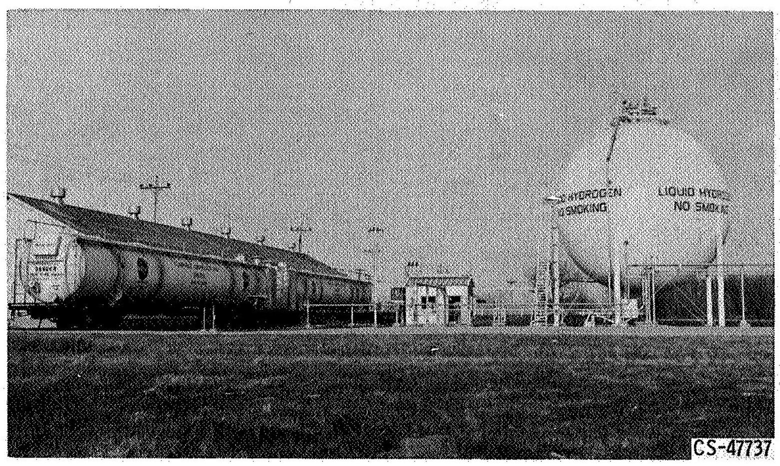

Figure 9-15. - Plum Brook liquid-hydrogen storage facility.

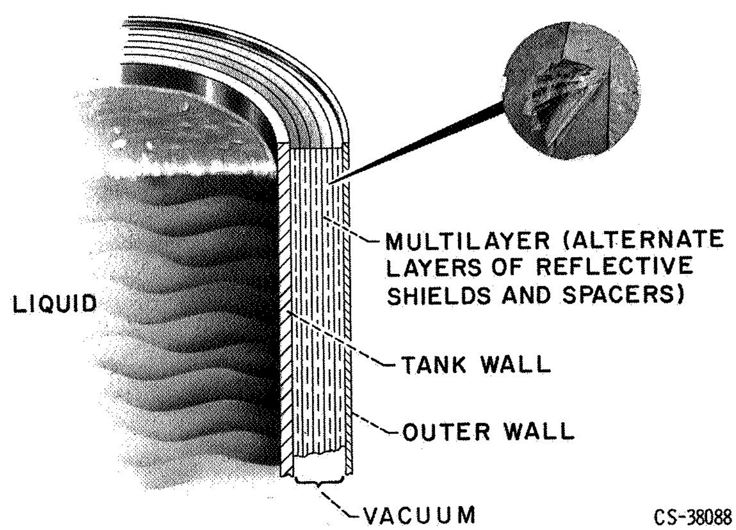

Figure 9-16. - Multilayer insulation.

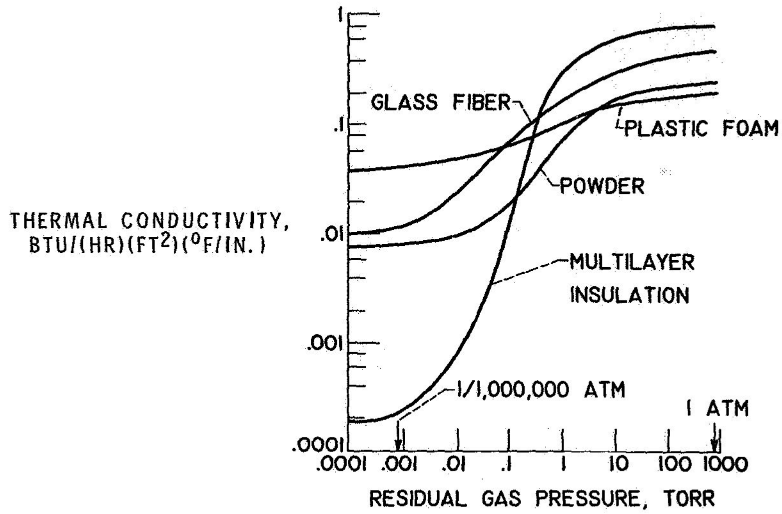

Figure 9-17. - Effect of residual gas pressure.

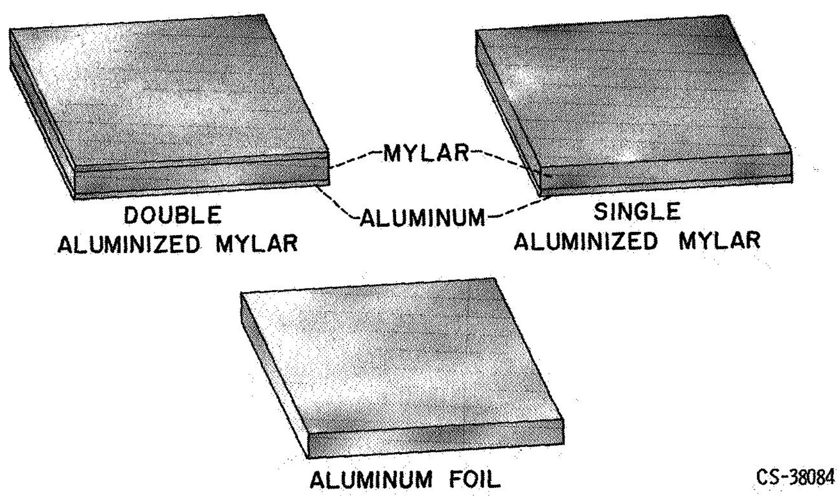

Figure 9-18. - Multilayer insulation reflective shields.

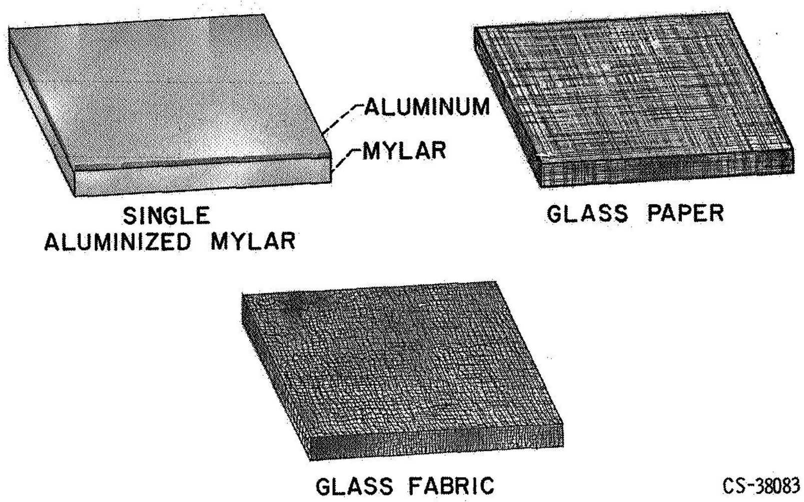

Figure 9-19. - Spacer materials in current use.

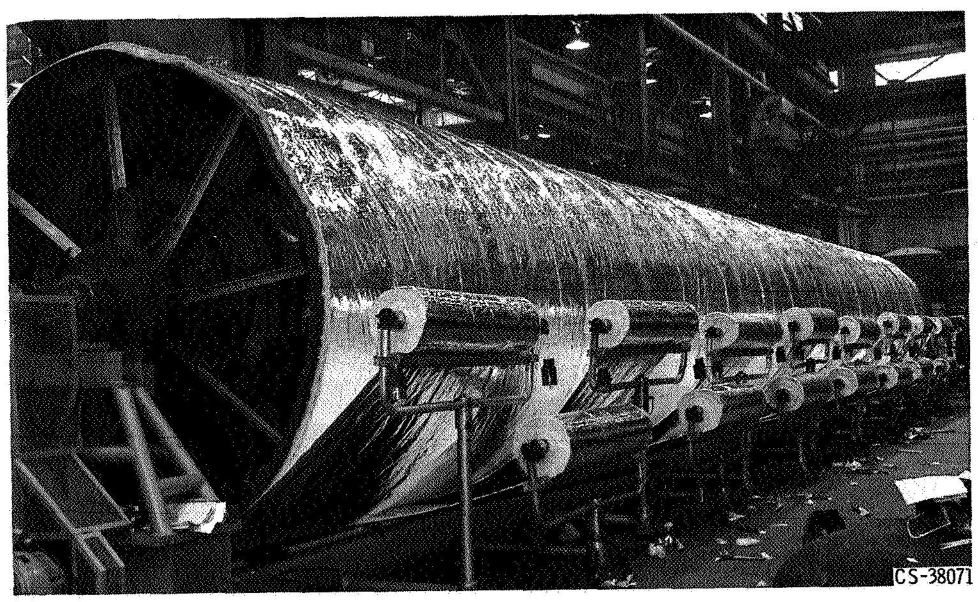

Figure 9-20. - Machine winding of multilayer insulation. (Courtesy Linde Div., Union Carbide Corp.)

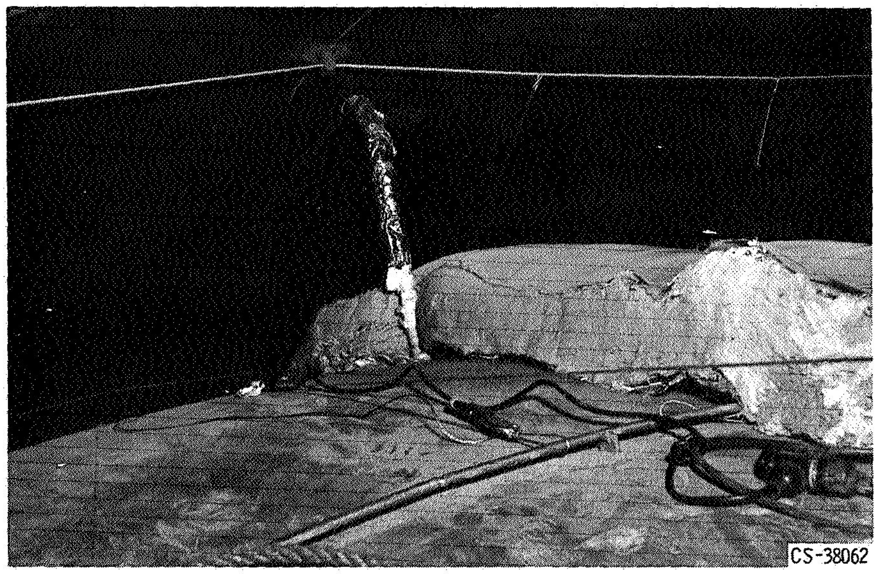

Figure 9-21. - Application of multilayer insulation to ground storage tank.

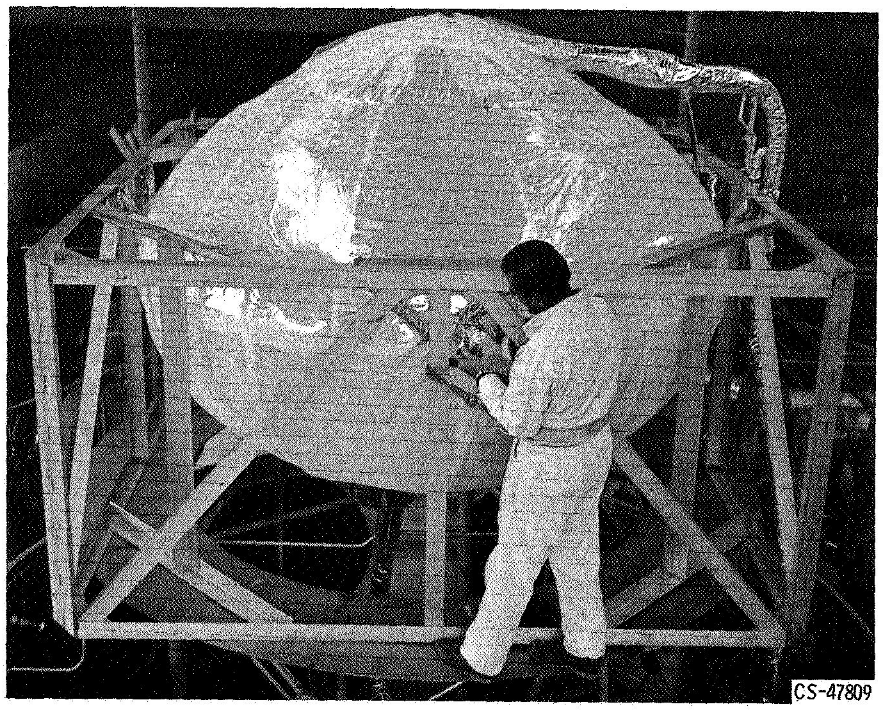

Figure 9-22. - Insulation of 9-foot-diameter liquid-hydrogen tank. (Courtesy Lockheed Missiles & Space Co.)

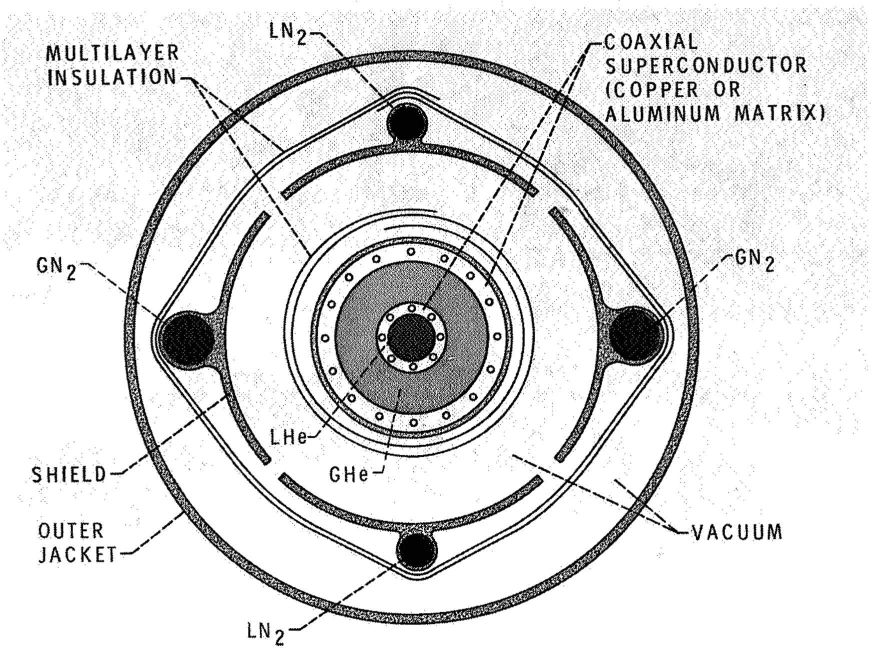

Figure 9-23. - Conceptual model of superconducting power transmission line.

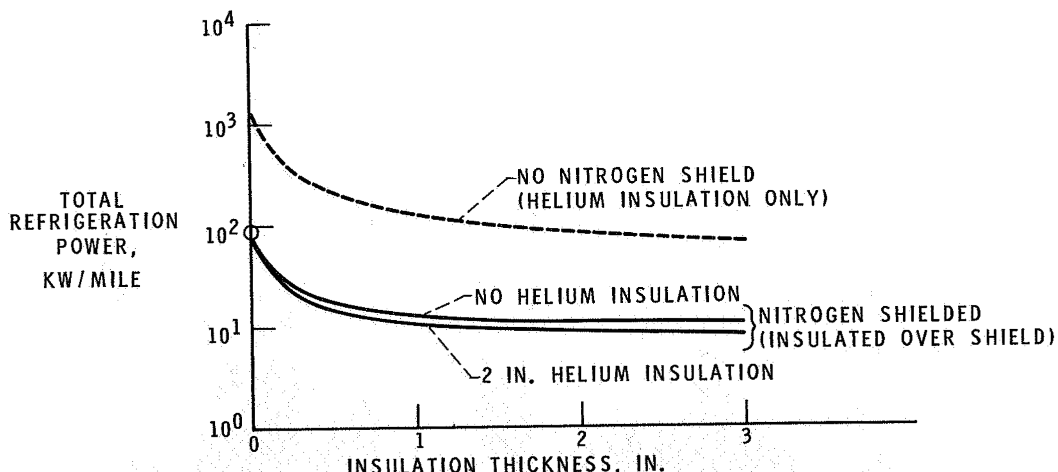

Figure 9-24. - Effect of insulation on refrigeration power for 2-inch liquid-helium line.